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Accuracy assessment of the MODIS snow products†

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Abstract:

A suite of Moderate-Resolution Imaging Spectroradiometer (MODIS) snow products at various spatial and temporal resolutions from the Terra satellite has been available since February 2000. Standard products include daily and 8-day composite 500 m resolution swath and tile products (which include fractional snow cover (FSC) and snow albedo), and 0·05° resolution products on a climate-modelling grid (CMG) (which also include FSC). These snow products (from Collection 4 (C4) reprocessing) are mature and most have been validated to varying degrees and are available to order through the National Snow and Ice Data Center. The overall absolute accuracy of the well-studied 500 m resolution swath (MOD10_L2) and daily tile (MOD10A1) products is ~93%, but varies by land-cover type and snow condition. The most frequent errors are due to snow/cloud discrimination problems, however, improvements in the MODIS cloud mask, an input product, have occurred in 'Collection 5' reprocessing. Detection of very thin snow (<1 cm thick) can also be problematic. Validation of MOD10_L2 and MOD10A1 applies to all higher-level products because all the higher-level products are all created from these products. The composited products may have larger errors due, in part, to errors propagated from daily products. Recently, new products have been developed. A fractional snow cover algorithm for the 500 m resolution products was developed, and is part of the C5 daily swath and tile products; a monthly CMG snow product at 0·05° resolution and a daily 0·25° resolution CMG snow product are also now available. Similar, but not identical products are also produced from the MODIS on the Aqua satellite, launched in May 2002, but the accuracy of those products has not yet been assessed in detail. Published in 2007 by John Wiley & Sons, Ltd.

KEY WORDS MODIS; snow covered area; snow products; Terra; Aqua

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INTRODUCTION

Snow may cover up to about 50 million km^2 of the Northern Hemisphere land surface (http://climate.rutgers.edu/snowcover/) and thus has a major impact on the Earth's energy balance because of its high albedo and low thermal conductivity. Albedo, the ratio of reflected to incident solar energy, governs how much solar energy is absorbed by land and ocean surfaces, and can change dramatically, for example from 0·2 to 0·8 or greater, when snow first accumulates. Snow cover also has a major influence on atmospheric circulation by modifying overlying air masses.

Because so much of the water supply used by humans comes from snow cover, especially in mountainous areas throughout the world, snow water equivalent (SWE) is a critical snowpack parameter. However SWE cannot yet be measured remotely with the accuracy required by hydrologic models. To obtain accurate SWE estimates from space, other sources of information, including station data and snow-covered area, should be used, together, to increase their usability in land-surface models.

Moderate-Resolution Imaging Spectroradiometer (MODIS) data, available since 2000, have proven useful for a large variety of land, ocean and atmospheric applications, and a multitude of MODIS standard products is now available. The MODIS standard snow-cover products–providing snow extent and albedo–are useful, or potentially useful, as input to models. The accuracy of these snow products must be known in order to optimize their use.

Two types of validation are addressed in this paper–absolute and relative. To derive absolute validation, the MODIS maps are compared with ground measurements or measurements of snow cover from Landsat data, which are considered to be the 'truth' for this work. Relative validation refers to comparisons with other snow maps, most of which have unknown accuracy. Thus for the studies of relative validation, it is not generally known which snow map has a higher accuracy.

In this paper, we provide the most up-to-date information on the accuracy of each MODIS-derived standard snow cover product in collection 4 (C4 or Version 4 (V004)). C4 refers to the fourth reprocessing of the data-product suite (or the second complete reprocessing). The products have varying degrees of maturity, and because of the different spatial and temporal resolutions, the accuracy is different for different products. Though the focus is on the C4 products derived from the MODIS

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on the Terra satellite, denoted by MOD10, Aqua MODIS products, designated MYD10, are also discussed.

BACKGROUND

MODIS is an imaging spectroradiometer that employs a cross-track scan mirror, collecting optics, and a set of detector elements to provide imagery of the Earth's surface and clouds in 36 discrete, narrow spectral bands from approximately 0·4 to 14·0 μm (Barnes *et al.*, 1998) http://modis.gsfc.nasa.gov/. The spatial resolution of the MODIS instrument varies with spectral band, and ranges from 250 m to 1 km at nadir.

Operational data collection from the Terra MODIS began on 24 February 2000, orbiting in a 10 : 30 A.M. local time descending node and from the Aqua MODIS on 24 June 2002, in a 1 : 30 P.M. local time ascending node. Together, the two overpass times (Terra in the morning and Aqua in the afternoon) allow the possibility of diurnal observations of snow, and the possibility to obtain more clear views of the surface, as clouds can change in position and extent within a period of 3 h. MODIS instruments on each spacecraft are nearly identical except with respect to band 6 (1·628–1·672 μm). Approximately 70% of the band-6 detectors are non-functional on the Aqua MODIS. Since MODIS band 6 is crucial for snow detection, the loss of band 6 detectors forced a change in the Aqua snow mapping algorithms to use band 7 (2·105–2·155 μm) where band 6 is used in the Terra MODIS algorithms. There are implications concerning the accuracy of the Aqua snow cover products and this is discussed later.

The MODIS snow and sea ice products (http://modis-snow-ice.gsfc.nasa.gov), available globally, are provided at a variety of different resolutions and projections to serve different user groups (Hall *et al.*, 2002a, 2004, 2006; Riggs *et al.*, 2006), and are distributed through the National Snow and Ice Data Center in Boulder, Colorado (Scharfen *et al.*, 2000). The snow maps are available at 500 m resolution on a sinusoidal projection, and at 0·05° and 0·25° resolution on a latitude/longitude grid known as the climate-modelling grid (CMG). (The 0·25° resolution daily snow maps are available as flat-binary files on a geographic grid, from the data-product developers).

Collection 4 (C4) reprocessing was completed in July 2004, for MODIS land products. C4 spans the period for the Terra MODIS from February 24, 2000, to the present, and for the Aqua MODIS from June 2002, to the present. The current reprocessing of MODIS data known as 'Collection 5' or C5, began in mid-July 2006. The reprocessing will proceed forward in time beginning from 24 February 2000, and is scheduled to be completed in September 2008.

The primary difference between C4 and C5 products results from improvements in the cloud-mask product in C5, thus permitting more snow cover to be mapped, and from improved screening for erroneous snow.

MODIS SNOW PRODUCT SUITE OVERVIEW

The MODIS snow product suite is produced as a sequence of products beginning with the 500 m resolution swath product (Table I). Each succeeding product inherits its quality and errors from the preceding product. A brief description of the snow algorithms and products is given in the following sections. The basics of the algorithm are described here as they are relevant to the quality, accuracy and use of the product, and higher-level products.

There are several different data-product levels starting with Level 2 (L2). An L2 product is a geophysical product that remains in its original image swath format, with the latitude and longitude known precisely; it has not been temporally or spatially manipulated. A Level-2G (L2G) product has been gridded onto a global sinusoidal map projection as a series of 10° latitude by 10° longitude adjoining 'tiles,' each tile being a piece, e.g. area, of a map projection. Level-2 data products are gridded into L2G tiles by mapping the L2 pixels into cells of a tile in the map projection grid. The L2G algorithm creates a gridded product necessary for development of the Level-3 (L3) products. An L3 product is a geophysical product that has been temporally and/or spatially manipulated. A full description of this is provided in the MODIS Snow Products User Guide (Riggs *et al.*, 2006) http://modis-snow-ice.gsfc.nasa.gov/userguides.html.

In Table I, an asterisk indicates a product or part of a product available only in C5. Fractional snow cover (FSC) applies only to the FSC in or from MOD10_L2 and MOD10A1. The MOD10C1 and higher products have fractional snow cover based on a different method of calculation and are in both C4 and C5.

SWATH LEVEL SNOW MAPPING ALGORITHM

The automated MODIS snow mapping algorithm uses at-satellite reflectance in MODIS bands 4 (0·545–0·565 μm) and 6 (1·628–1·652 μm) to calculate the normalized difference snow index (NDSI). (Bands 4 and 7 are used to calculate the NDSI for the Aqua MODIS.) Prior to the development of this algorithm for MODIS, the basic technique had been used previously to map snow using Landsat data (for example, Crane and Anderson, 1984; Dozier, 1989):

$$\mathrm{NDSI} = \frac{\text{band } 4 - \text{band } 6}{\text{band } 4 + \text{band } 6} \tag{1}$$

In addition to the NDSI, many other threshold tests are used and are described in many earlier publications (e.g. Hall *et al.*, 1995, 2002a), the Algorithm Theoretical Basis Document (ATBD) http://modis-snow-ice.gsfc.nasa.gov/atbd.html (Hall *et al.*, 2001a), and the Snow Product User Guide (Riggs *et al.*, 2006).

The algorithms use the MODIS bands listed in Table II to map snow cover and snow albedo.

The MODIS snow cover algorithms use the following MODIS products as input: the MODIS (Level 1B) radiance data (Guenther *et al.*, 2002), the MODIS cloud

Table I. MODIS snow-data products available in Collections 4 and 5; for the Earth Science Data Type (ESDT), MOD refers to the Terra MODIS and MYD refers to the Aqua MODIS products. FSC denotes fractional snow cover

Long name	Earth science data type (ESDT)	Spatial resolution
MODIS/Terra Snow Cover 5-Min L2 Swath 500 m (includes FSC[a])	MOD10_L2	500 m resolution, swath of MODIS data
MODIS/Terra Snow Cover Daily L3 Global 500 m SIN Grid (includes FSC[a] and snow albedo)	MOD10A1	500 m resolution, projected, gridded tile data
MODIS/Terra Snow Cover 8-Day L3 Global 500 m SIN Grid	MOD10A2	500 m resolution, projected, gridded tile data
MODIS/Terra Snow Cover Daily L3 Global 0·05° CMG	MOD10C1	0·05° resolution, lat/lon climate modelling grid
MODIS/Terra Snow Cover 8-Day L3 Global 0·05° CMG	MOD10C2	0·05° resolution, lat/lon climate modelling grid
MODIS/Terra Snow Cover Monthly L3 Global 0·05° CMG	MOD10CM[a]	0·05° resolution, lat/lon climate modelling grid
MODIS/Terra Snow Cover Daily Global 0·25° CMG[b]	MOD10C1C[c]	0·25° resolution, lat/lon climate modelling grid
MODIS/Aqua Snow Cover 5-Min L2 Swath 500 m (includes FSC[a])	MYD10_L2	500 m resolution, swath of MODIS data
MODIS/Aqua Snow Cover Daily L3 Global 500 m SIN Grid (includes FSC[a] and snow albedo)	MYD10A1	500 m resolution, projected, gridded tile data
MODIS/Aqua Snow Cover 8-Day L3 Global 500 m SIN Grid	MYD10A2	500 m resolution, projected, gridded tile data
MODIS/Aqua Snow Cover Daily L3 Global 0·05° CMG	MYD10C1	0·05° resolution, lat/lon climate modelling grid
MODIS/Aqua Snow Cover 8-Day L3 Global 0·05° CMG	MYD10C2	0·05° resolution, lat/lon climate modelling grid
MODIS/Aqua Snow Cover Monthly L3 Global 0·05° CMG	MYD10CM[a]	0·05° resolution, lat/lon climate modelling grid

[a] C5 only.
[b] Not yet a MODIS *standard* product; but available through the snow and ice project's data-product developers: http://modis-snow-ice.gsfc.nasa.gov/.
[c] Unofficial ESDT; the ESDT is not official until the product is designated as a *standard* product.

Table II. MODIS bands used to produce the MODIS snow products

Band number	Bandwidth (μm)	Terra and/or Aqua
1	0·62–0·67	Terra & Aqua
2	0·841–0·876	Terra & Aqua
3	459–479	Terra & Aqua
4	0·545–0·565	Terra & Aqua
5	1230–1250	Terra & Aqua
6	1·628–1·672	Terra
7	2·105–2·155	Aqua
31	10·780–11·280	Terra & Aqua
32	11·770–12·270	Terra & Aqua

mask (Ackerman *et al.*, 1998; Platnick *et al.*, 2003), and the MODIS geolocation product for latitude and longitude, viewing geometry data and the land/water mask (Wolfe *et al.*, 2002).

Daily snow cover, including FSC, is produced at 0·05°–0·25° resolution (Table I) in C4. FSC within a CMG cell is based on the area of snow cover mapped into each cell from the 500 m resolution snow cover tile product.

Using an algorithm developed by Salomonson and Appel (2004), FSC is provided in the MOD10_L2 swath and the MOD10A1 snow maps at 500 m resolution in C5. (An Aqua-specific FSC algorithm (Salomonson and Appel, 2006) is also available in C5.) The FSC algorithm is based on a statistical-linear relationship developed between the NDSI from MODIS and the true sub-pixel fraction of snow cover as determined using Landsat scenes from Alaska, Canada and Russia. The fraction of snow cover within a MODIS 500 m resolution pixel is provided with a mean absolute error of less than 0·1 over the entire range of FSC from 0·0–1·0 (Salomonson and Appel, 2004).

Changes that occur in the spectra of a forest stand as it becomes snow covered can be exploited to map snow cover in forests. For the MODIS algorithm, a feature was developed by Klein *et al.* (1998) to enable more snow to be mapped in forested areas. The primary change in reflectance occurs in the visible wavelengths as snow has a much higher visible reflectance than soil, leaves or trees. A fundamental change that snow cover causes in the spectral response of a forest, which can be used in a global algorithm, is that the reflectance in the visible part of the spectrum will often increase with respect to the near-infrared reflectance. This behaviour is captured in the normalised difference vegetation index (NDVI) (Townshend *et al.*, 1993), as snow cover will tend to lower the NDVI. MODIS bands 1 and 2 are used to calculate the NDVI for the Terra MODIS products. The NDVI and NDSI are used together to improve snow mapping in dense forests. If the NDVI = ~0·1, the pixel may be mapped as snow even if the NDSI is <0·4 (Klein *et al.*, 1998). Because of the need to use Band 7 instead of Band 6 for the Aqua MODIS products, this part of the basic snow mapping algorithm is not available for the Aqua MODIS products.

COLLECTION 5 (C5) CHANGES

A few changes in the algorithms and data products were made for C5. The most notable changes are the implementation of the FSC algorithm in MOD10_L2 and mapping that fractional snow into the MOD10A1 product, and the consistent application of screens to reduce the occurrence of erroneous snow in various snow-covered places in the MOD10_L2 algorithm. A code bug that identified snow-covered lakes as land was corrected in the MOD10A2 algorithm. In addition, improvements in the cloud mask input products MOD 35 and MYD 35, permit more snow to be mapped if it is present.

Internal compression is applied to all the L3 and higher products in C5 and should be transparent to users, but could possibly cause difficulties for some users of the L2 product. The L2 products were compressed post-production using the hrepack algorithm. Interested users should refer to the C5 User Guide (Riggs *et al.*, 2006) for information on how to handle the hrepack compression and for other minor changes made in the products for C5.

VALIDATION STAGES AND DATA-PRODUCT LEVELS FOR MODIS PRODUCTS

Accuracy of the MODIS products has been achieved at various levels or 'stages.' A 'beta' product is the first publicly available version of a product. Beta products are minimally validated and may contain significant errors. A 'provisional' product is partially validated; these are early science-validated products and are useful for exploratory and some scientific studies. For a 'validation stage 1' product, accuracy has been estimated using a small number of independent measurements from selected locations and time periods. The accuracy of a 'validation stage 2' product has been assessed by a number of independent measurements, at a number of locations or times representative of the range of conditions. In a 'validation stage 3' product, the accuracy has been assessed by independent measurements in a systematic and statistically robust way representing global conditions.

SWATH SNOW COVER PRODUCT (MOD10_L2)

The snow data product sequence begins with a 5-min swath of Terra MODIS data (MOD10_L2) (Figure 1) at a spatial resolution of 500 m and covering 2330 km (cross track) by 2030 km (along track). Coarse-resolution, 5-km latitude and longitude data are stored as separate data layers in the product to provide geographic reference. Only pixels that cover land or inland water, are unobstructed by clouds (according to the MODIS cloud-mask product) and are in daylight are analysed for the presence or absence of snow. The product provides a thematic map of snow-covered land, snow free land, cloud (from the MODIS cloud mask, MOD35) and water (from the land/water mask). The MOD10_L2 products are validated at stage 2.

Absolute validation

Since the swath product is the first of the sequence of products, validation of this product is applicable to all of the higher-level products. Numerous studies have been conducted using the MOD10_L2 swath snow maps in which snow mapping results have been compared with ground and station data (absolute accuracy), and other snow maps (relative accuracy). The absolute accuracy of this product is generally >93%, depending on the land cover (Hall *et al.*, 2001b; Simic *et al.*, 2004; Ault *et al.*, 2006). Errors of omission are greatest when only trace amounts of snow are present.

The most significant factor affecting snow detection error is snow/cloud discrimination. The amount of error caused by snow/cloud confusion is relatively small, quantitatively, but the qualitative error is such that a few erroneous snow pixels have a large visual impact when seen on the resulting snow map. Snow/cloud confusion errors are typically associated with cloud-shadowed land and thin, sparse snow cover. The error may be caused either by identifying cloud as snow if the cloud is not identified as certain cloud in the cloud mask or, more commonly, by missing snow possibly because thin, sparse snow cover was identified as cloud in the cloud mask. Improvement has been made at reducing the snow/cloud confusion in the C5 MODIS cloud mask which in turn reduces error in the snow algorithm. Some erroneous snow mapping, ranging from 0·001 to 2% depending on amount, type and mix of clouds in a swath, originating from snow/cloud confusion remains in C5.

Another source of false snow detection which is related to the problem of thin snow, is snow/cloud confusion that occurs at the edges of a snow-covered area. An example of this problem is shown in the snow map of the image pair (Figure 1) showing the result of a snowstorm in Colorado where there is snow/cloud confusion in the thin snow at the edges of the snowpack.

Extensive assessment of the accuracy of the swath product was conducted by Ault *et al.* (2006) in the lower Great Lakes region of the United States. Using both National Weather Service (NWS) Cooperative Observation Station data and field observations collected by students and teachers, they studied the accuracy of MOD10_L2 in this mixed agriculture and forest land-cover class and found an overall absolute accuracy of ~93%, in agreement with accuracy assessments by Hall *et al.* (2001b) in similar land covers. Accuracy was found to be 96% when no snow was present, but only 41% when trace (<10 mm depth) amounts of snow were reported (Ault *et al.*, 2006). It is extraordinarily difficult

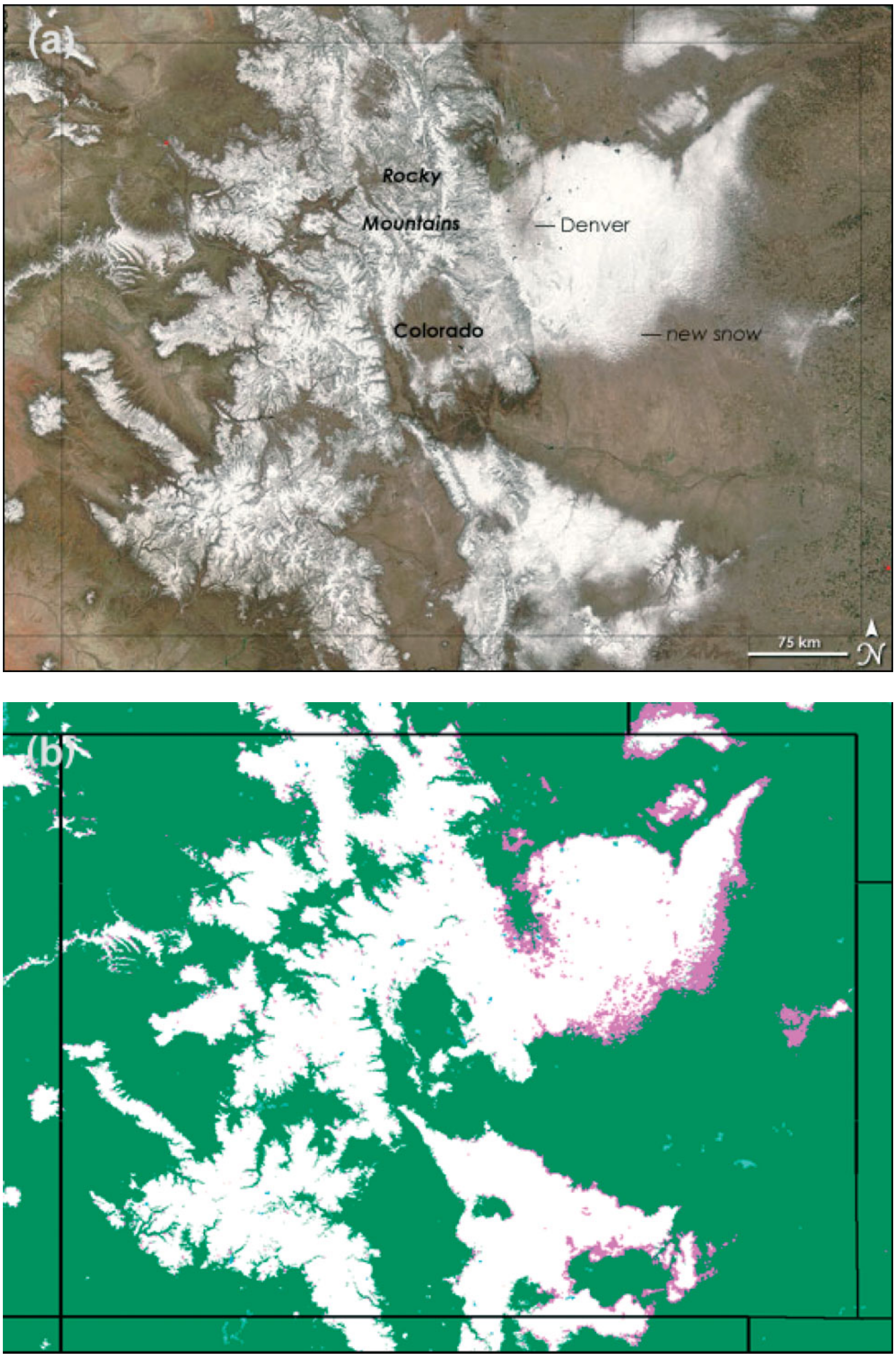

Figure 1. (a) Moderate-Resolution Imaging Spectroradiometer true-colour image acquired on 12 April 2005, showing the result of a new snowfall in Colorado; (b) the corresponding swath snow map (MOD10_L2). The areas mapped as 'cloud' surrounding the snow cover represent a problem with snow/cloud discrimination as discussed in the text. Courtesy of NASA's Earth Observatory and the MODIS Snow and Ice Team http://modis-snow-ice.gsfc.nasa.gov/041205co.html

to do an accurate assessment of a snow cover product when only trace amounts of snow are present because the snow may not cover a large percentage of a pixel and may not exhibit a strong spectral signature and, unless the ground truth is done at the exact time of the satellite overpass, traces of snow may melt and not be detected. Ideally, ground measurements must be coordinated to nearly the exact time of the satellite overpass and must be conducted over a large enough area of cover more than 50% of a pixel. This is a nearly impossible task.

Relative validation

The MOD10_L2 swath snow maps were compared against the snow maps from the *SnowStar* operational snow mapping system in Scandinavia. *SnowStar* is an operational snow mapping system developed in Norway for mapping snow in Scandinavia (Andersen, 1982;

Solberg and Anderson, 1994). The *SnowStar* maps were modified to use 250 m band 1 MODIS data as input and a cloud mask that is tuned to the Fenoscandia region (Finland, Sweden and Norway). The MODIS snow maps, and the modified *SnowStar* maps were compared for four different dates in the melt season of 2004 (April 12, 21, 24 and May 1) in the Fenoscandia region. Because the *SnowStar* maps employ 250 m resolution data, are tuned specifically to the region, and the cloud mask is manually prepared, the *SnowStar* maps are closer to the actual snow conditions than are the MODIS snow map products, and for the purposes of this study, are considered the 'truth.'

For 12 April 2004, the *SnowStar* map shows that 24·7% of the scene is snow covered, while the MODIS map shows that 19·2% of the scene is snow covered (Figure 2a and b) (Hall *et al*., 2004). When the same cloud mask was used on both maps (cloud masks from both the MODIS map product and from the *SnowStar* map) and using the *SnowStar* land/water mask on both maps, the *SnowStar* map shows somewhat less snow as compared to the MODIS map product — 15·62% of the scene is snow covered while the MODIS product shows that 17·75% of the scene is snow covered (Figure 2c and d). The result from this study shows that the regionally tuned cloud mask and coastline contribute to significant improvements in the snow mapping result using the *SnowStar* algorithm, but the MODIS and *SnowStar* maps would be comparable if the cloud mask and coastline inputs to the MODIS algorithm were improved (Hall *et al*., 2004).

Many other MODIS-derived algorithms to calculate binary and FSC have also been developed (e.g. Anttila *et al*., 2006), but cannot be described in detail in this paper.

All of the higher-level snow products emanate from the swath product, MOD10_L2, and therefore, the validation of the swath snow products is relevant to all other products. Most users employ the daily tile product, discussed below.

MODIS DAILY SNOW COVER TILE PRODUCTS (MOD10A1) AND MODIS 8-DAY COMPOSITE SNOW COVER TILE PRODUCTS (MOD10A2)

The second in the sequence, the 500 m resolution daily snow cover tile product, MOD10A1, is generated by mapping pixels from the swath product to their geographic locations in a MODIS-specific global sinusoidal projection (see Wolfe *et al*. (2002) for information on the sinusoidal projection). MOD10A1 is generated from the MOD10_L2 swath product in the following manner: one pixel from observations of a day is selected as the best observation based on a 'scoring' algorithm that selects the observation nearest to local noontime, closest to nadir with maximum coverage of the cell.

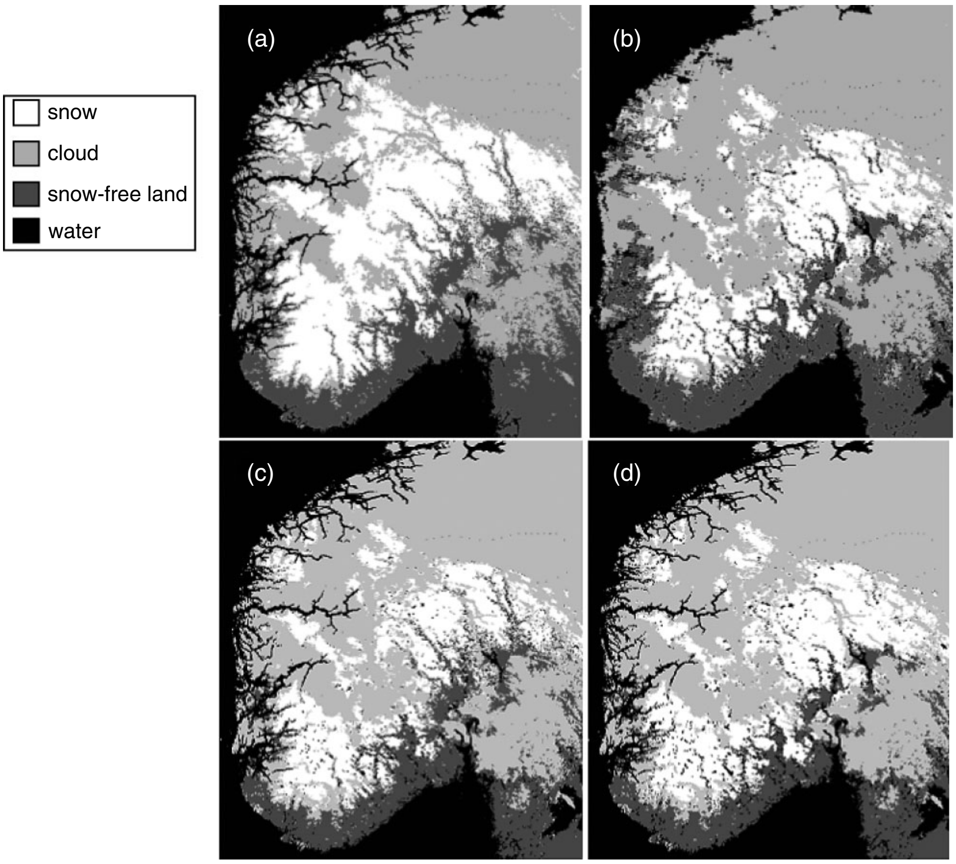

Figure 2. Comparison of the *SnowStar* snow map (Figure 2a) with the MOD10_L2 swath snow map (Figure 2b) and of the Fenoscandia region; note the difference in the cloud masks. Figure 2c and d show the *SnowStar* and MODIS maps, respectively, with a combined MODIS-*SnowStar* cloud mask and *SnowStar* land-water mask overlaid on each

The 8-day composite maximum snow cover tile product, MOD10A2, is produced for each tile by compositing 8 days of the daily tile products. If snow had been mapped on any day in any location on the daily tile product, it is classified as snow covered in the 8-day composite, thus the composite represents maximum snow cover during the 8-day period. Days on which snow was observed are also recorded in the product. Eight-day periods are fixed, begin on the first day of each year, and may extend into the following year, but in each new year, the 8-day period starts over again on 1 January.

Both the MOD10A1 and MOD10A2 products are validated at stage 2 with the exception of the daily snow albedo (discussed later), a data layer in MOD10A1, which is currently at the provisional stage.

Absolute validation

The MOD10A1 MODIS snow products showed an overall accuracy of 94·2% compared with 15 SNOpack TELemetry (SNOTEL) sites in a study done by Klein and Barnett (2003), in which they used National Operational Hydrological Remote Sensing Center (NOHRSC) and MODIS snow maps and SNOTEL measurements in the upper Rio Grande basin for the 2000–2001 snow season. (SNOTEL is an automated system to collect snowpack and related data in the western United States.) A time-series comparison between MODIS retrievals and SNOTEL measurements over the entire snow season showed an overall classification accuracy for MODIS of 88%; the errors of commission and omission were found to be 12 and 15%, respectively, with most of the discrepancies occurring early and late in the snow season in thin snowpack conditions. The MOD10A1 product showed higher accuracy (94·2%) with SNOTEL than did the NOHRSC product (75·9%), and the two products agreed 86% of the time (Klein and Barnett, 2003) (Figure 3).

Also, in the upper Rio Grande river basin Zhou *et al.* (2005) studied both the daily (MOD10A1) and 8-day composite (MOD10A2) snow maps from February 2000 through June 2004. Their results showed that overall, the 8-day product had a higher correlation ($r = -0{\cdot}404$) with streamflow and a lower percentage of spurious snowmelt events in the winter than did the daily product ($r = -0{\cdot}300$). The reason for the problem in the daily product is cloud contamination—when only clear areas were studied, the accuracy of the daily product was greater than that of the 8-day product. Zhou *et al.* (2005) also found that both the daily (MOD10A1) and 8-day (MOD10A2) products had a low omission error (misclassifying snow as non-snow covered land).

Maurer *et al.* (2003) compared MODIS and NOHRSC data for 46 days in the Columbia river basin, and 32 days in the Missouri river basin during the winter and spring of 2000–2001. The presence or absence of snow was determined from meteorological station data. On average, MODIS snow maps classified fewer pixels as cloud as compared to NOHRSC snow maps thus permitting 15% more of the Columbia river basin area to be classified as to the presence or absence of snow using the MODIS maps.

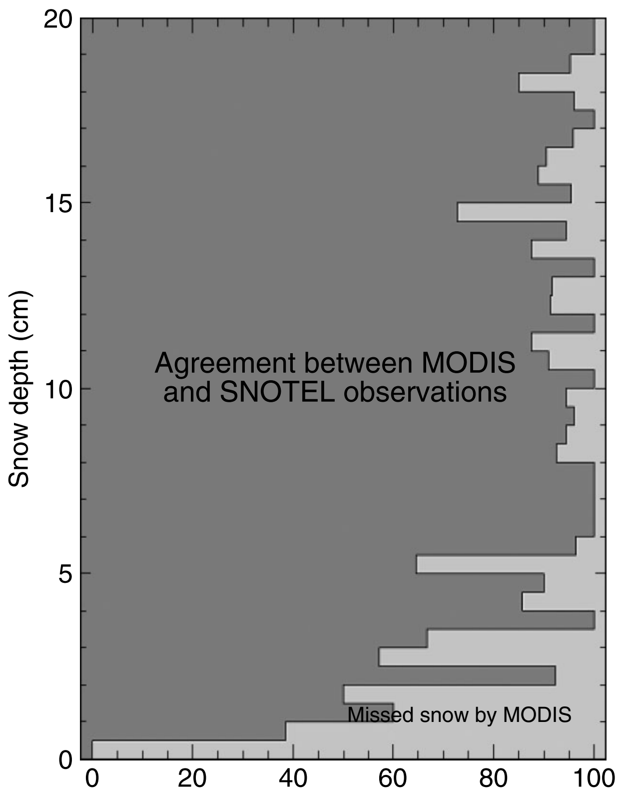

Figure 3. Percent agreement between MODIS snow retrievals and SNOTEL observations as a function of snow depth. Comparisons are illustrated for all cloud-free days at 15 SNOTEL sites for the period 1 October 2000, to 9 June 2001 (From Klein and Barnett, 2003)

MOD10A1 snow cover maps acquired over Canada were compared with observations from almost 2000 meteorological stations by Simic *et al.* (2004). The lowest agreement of all the land-cover types studied was found in evergreen forests, in agreement with earlier studies (for example, Hall *et al.* (2001b)). Overall, the MOD10A1 results exhibited an average percentage agreement of 93% with the *in situ* data over a 160-day period in 2001, with the evergreen forests showing the lowest percentage agreement (80%) where the MOD10A1 maps tended to overestimate snow cover, with the closed canopy evergreen forests showing consistently poorer agreement than did the open canopy evergreen forests (Figure 4). The agreement between the MODIS snow maps and the meteorological station data was generally found to be lower during the early part of the snow season (January to June 2001) and during snow melt particularly in forested areas (Simic *et al.*, 2004). In addition, Wang *et al.* (2005) show that the NOAA NESDIS (Ramsay, 1998) snow product also has difficulties mapping snow cover over higher latitudes of Canada by consistently overestimating snow cover during the spring melt period.

A limitation of the MOD10A2 and all of the higher level composited products, such as MOD10A2, is that persistent cloud cover over consecutive days or all days of the period can hide snow cover that may have existed

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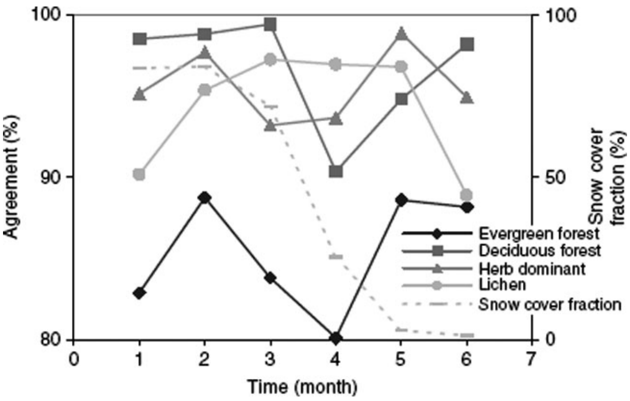


Figure 4. Snow cover mapping assessment of the MODIS snow product over Canada from January to June 2001 (From Simic *et al*., 2004)

during some or all of the period. For example, if the clouds responsible for a snow event do not clear before the end of the compositing period, then snow cover will not be mapped during the 8-day period during which it fell. In that situation the MOD10A2 product will show, erroneously, bare ground for that area, assuming there was no snow visible before that late-period snowfall.

Daily snow albedo

Daily snow albedo, currently a provisionally validated product, is provided as a data layer in MOD10A1. This product (Klein and Stroeve, 2002) produces daily albedo values of pixels determined to be snow covered by MOD10A1, and uses the MODIS cloud mask, MOD35, and atmospheric correction (Vermote *et al*., 2002). Models of the bi-directional reflectance of snow created using a discrete-ordinance radiative transfer (DISORT) model are used to correct for anisotropic scattering effects over non-forested surfaces. After the anisotropic corrections are performed, MODIS spectral albedo measurements are converted to broadband albedo values by the method of Liang (2000). Some validation has been accomplished on the albedo product over Fort Peck, Montana (Klein and Stroeve, 2002), Greenland and eastern Turkey.

Both Terra and Aqua daily snow albedo results were studied by Stroeve *et al*. (2006). Terra- and Aqua-derived albedos were correlated with automatic weather station (AWS) data from five stations on the Greenland Ice Sheet ($r = 0{\cdot}79$ and $r = 0{\cdot}77$, respectively). Stroeve *et al*. (2006) also concluded that the MOD10A1 and MYD10A1 daily albedo values track the seasonal variability in albedo on the Greenland Ice Sheet, but exhibit more temporal variability than observed at the stations.

MOD10A1-derived snow albedo maps were compared with ground-based albedo measurements (from measurements and AWS data) in the Karasu basin in the headwaters of the upper Euphrates river basin in eastern Turkey by Tekeli *et al*. (2006). They concluded that MODIS albedo values were generally about 10% greater than the *in situ* values in the Karasu basin, with closer agreement at higher elevations. Reasons cited for the discrepancy include the fact that data acquisition times were different between the MODIS and *in situ* measurements, and the fact that air temperatures near the freezing point caused melt events. At higher elevations, better agreement was found between MODIS snow albedo and ground observations. Lower air temperatures and a more continuous snow cover at the higher elevations may have contributed to improved correspondence there.

Relative validation

Validation studies often do not take advantage of the full resolution of the MODIS snow maps. To compare with lower-resolution maps, such as the 4-km resolution IMS maps, the resolution of the 500-m resolution MODIS maps is often degraded. While this makes two products easier to compare, it does not take advantage of the improved snow-mapping accuracy possible at the higher spatial resolution of the MODIS maps.

NOHRSC snow cover maps were compared with MODIS snow cover maps (MOD10A1) in the Pacific northwest and the Great Plains for 18 and 21 days, respectively, between March and June 2001 by Bitner *et al*. (2002). The MODIS 500 m resolution product was degraded to match the resolution of the NOHRSC product (1 km). The agreement was reported to be 94·2% in the study area in the Pacific northwest and 95·1% in the study area in the Great Plains. The best agreement between the maps was achieved during the winter when continuous snow conditions prevailed. Although the overall agreement was high, there were major differences in the locations of the snow being mapped mainly due to differences in snow mapping in forested areas. The MOD10A1 maps were found to map more snow in forests consistently and correctly, as compared to the NOHRSC maps. The largest disparity in snow cover mapping between the NOHRSC and MODIS maps was found at the edges of the snowpack where MODIS maps show more snow. The MODIS maps often map more snow at the edges of snow covered areas because several swaths may be mapped per day; if snow falls and melts within a few hours, MODIS is likely to capture it in the daily product. In mid-winter, the agreement between the products was found to be good.

Simic *et al*. (2004) showed that the average agreement of the MOD10A1 and NOAA Geostationary Operational Environmental Satellite (GOES) and Special Sensor Microwave/Imager (SSM/I) GOES + SSM/I products, with *in situ* data, was 93 and 92%, respectively, indicating that, at least for their study areas in Canada, the products are comparable in mapping snow cover. Additionally, the ability of the two products to map snow cover in evergreen forests was similar, with an 80 and 81% agreement with MODIS and NOAA maps, respectively.

The Meteorological Service of Canada snow-water equivalent (SWE) product (Goodison and Walker, 1995) was compared with MOD10A1 snow maps for various land covers in eastern and western Canada by Bussières *et al*. (2002). The snow products matched well in general in terms of snow cover (of course the MODIS does not provide SWE), but there were individual days when the MODIS maps mapped bare ground incorrectly when meteorological station data indicated the presence of shallow (1–2 cm) snow. Most of the errors of omission of snow cover occur under these circumstances—when snow cover is very thin.

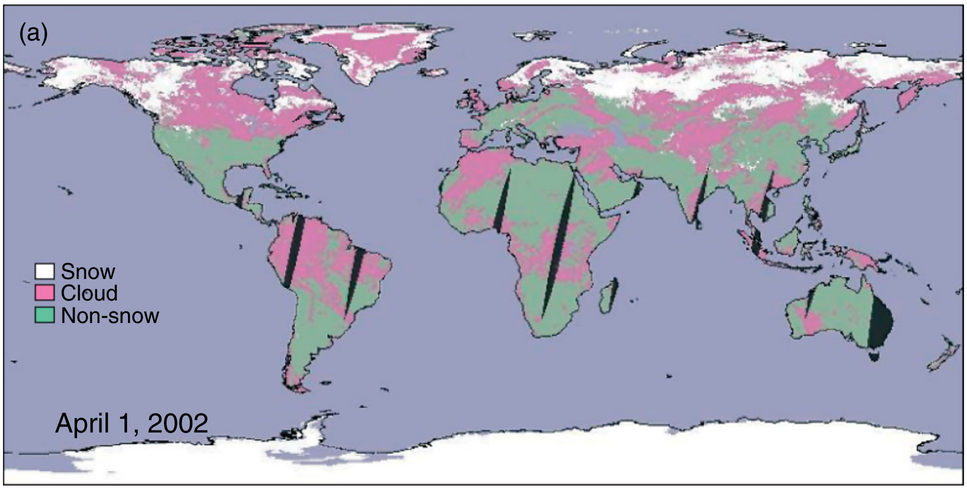
MODIS DAILY 0·05° CLIMATE-MODELLING GRID (CMG) PRODUCT (MOD10C1) AND MODIS 8-DAY COMPOSITE 0·05° CMG PRODUCT (MOD10C2)

The daily (MOD10C1) snow cover CMG map is generated on a geographic grid, by assembling all 320 MODIS land tiles from the daily 500 m snow product and binning the 500 m cell observations into the 0·05° CMG cells (Figure 5a). The binning technique creates an FSC array based on the number of snow observations in a grid cell, a fractional cloud-data array based on the number of cloud observations in each CMG grid cell, a confidence index (CI) and a Quality Assessment (QA) field (Riggs *et al*., 2006).

The 8-day composite (MOD10C2) map (Figure 5b) is produced from the 8-day tile product, MOD10A2. The product is generated by merging all the MOD10A2 tiles for an 8-day period and binning the 500 m data to 0·05° resolution CMG cells to create a global map of snow cover. Input values are binned into categories of snow, cloud, night, etc. The percentages of snow and cloud are computed, based on the binning results for each cell of the CMG, and written into the data arrays. Both the MOD10C1 and MOD10C2 products are validated at stage 2.

Errors of commission, like mapping snow where none exists, in the 8-day composite global maps have been found to be very low. In one study, errors of commission in Australia on three separate 8-day composite snow maps ranged from 0·02–0·10%. Because the maps are developed from composited daily maps, and errors propagate to the higher-level products, these errors of commission in the composite products are greater than those found in the daily maps.

As discussed earlier, snow cover may be missed especially when it occurs near the end of an 8-day compositing period. When there has been a snowstorm during an 8-day period, and if the sky remains cloudy for the remainder of the 8-day period, the MOD10C2 maps will fail to map snow over a very large area, incorrectly identifying it as snow free if it were snow free right before



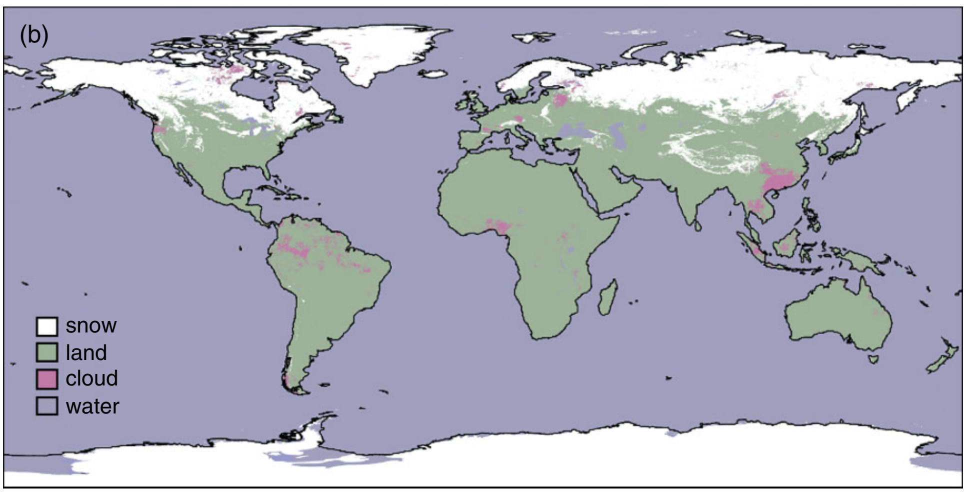


Figure 5. (a) MODIS daily snow map -1 April 2002 (MOD10C1). Fractional snow cover is available, but not shown. Figure 5b. MODIS 8-day snow map -6–13 April 2000 (MOD10C2). Fractional snow cover is available as part of the product, but not shown

the storm. If the clouds do not clear by the end of the 8-day period, the resulting snow cover from the snowstorm will not be mapped during the 8-day period in which the snow fell. This is not considered an error, but a limitation resulting from the inability of visible and near-infrared sensors to view the surface through cloud cover.

MODIS MONTHLY SNOW COVER MOD10CM

To compute the monthly Terra snow cover, MOD10CM (Figure 6), the mean FSC is computed for each cell from the daily CMG products for the month. If a daily CMG cell has 70% or more cloud-free observations, the cell will be used in the calculation of the monthly product. An average is then computed of the FSC in all the cells within the month. This monthly product is considered provisional and is available as a standard product in C5. Some comparisons with the Rutgers University Global Snow Lab (RUGSL) maps (Robinson, 1999) derived from the NOAA NESDIS interactive multisensor snow and ice mapping system (IMS) snow cover products have been undertaken, and preliminary results generally show a good correspondence. The RUGSL and MODIS monthly maps tend to agree better during the winter months and unsatisfactorily when snow is accumulating in the fall (Hall *et al*., 2004). The MODIS monthly snow cover product is an addition to the few existing monthly snow cover products available, and allow for intercomparison studies among products derived from different sensors and methods such as the NOAA IMS and RUGCL extent maps which are discussed in Wang *et al*. (2005). Currently the MODIS monthly snow product is provisional with respect to its validation status.

MODIS/TERRA SNOW COVER DAILY GLOBAL 0·25° GEOGRAPHIC CMG (NOT YET A STANDARD PRODUCT—TO BE DESIGNATED MOD10C1C)

The MODIS daily CMG map, MOD10C1, is generated at 0·05° resolution (about 5 km at the equator). However, current climate models typically run at 0·25° to 0·33° spatial resolution. In response to the modellers' spatial-resolution needs, a special daily-global FSC map at 0·25° resolution was created from MOD10C1. Figure 7 shows

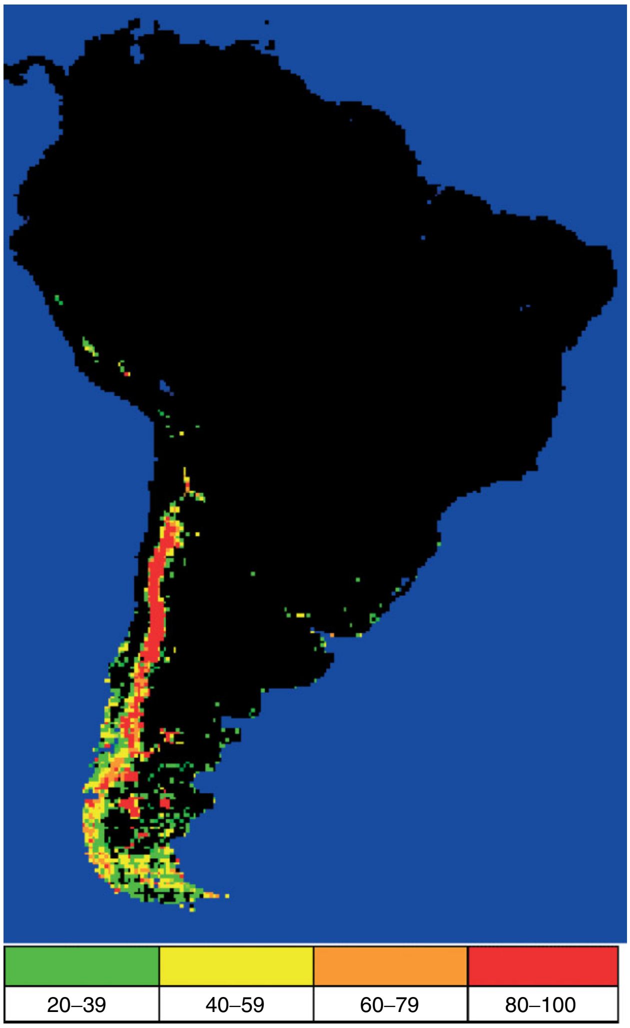


Figure 7. Moderate-Resolution Imaging Spectroradiometer (MODIS) snow map of South America—monthly maximum snow cover for July 2000 derived from MOD10C1C. Various colours represent different fractions of snow cover according to key

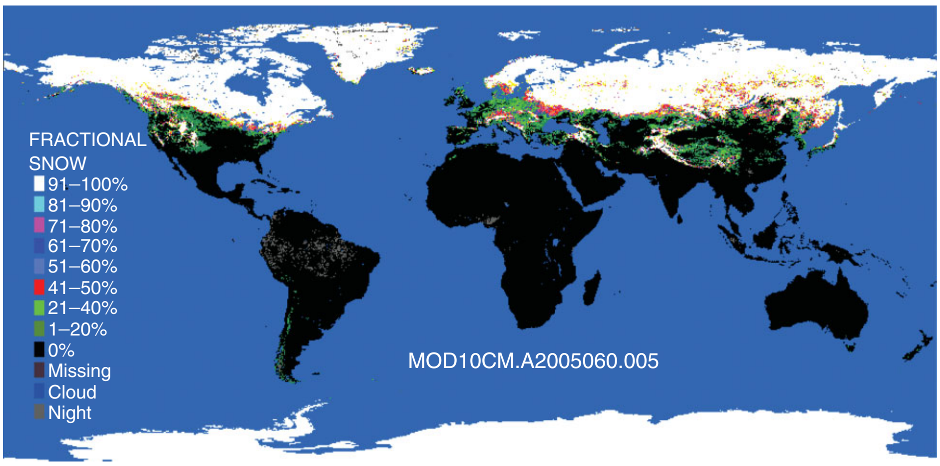


Figure 6. Moderate-Resolution Imaging Spectroradiometer (MODIS) monthly snow map—March 2005 (MOD10CM). Various colors represent different fractions of snow cover according to key

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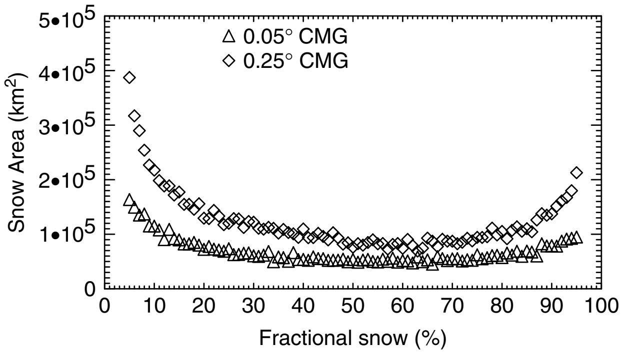

Figure 8. Comparison of snow areas between the two CMGs for the 5–95% fractional snow cover range—4 May 2004 (From Riggs *et al.*, 2005)

an example of the 0·25° resolution product for South America. Comparative analysis of the MODIS daily global FSC maps at 0·05° and 0·25° resolution shows that the general pattern of snow extent is very similar between the maps. However, extent of snow especially at high and low fractions, and at edges of snow-covered areas, can vary considerably (Riggs *et al.*, 2005). Prior to development of this product, some researchers were creating their own 0·25° resolution product (for example, Brubaker *et al.*, 2005). The MOD10C1C product is produced as flat-binary files and is available via DVD through the data-product developers [http://modis-snow-ice.gsfc.nasa.gov/].

In general, the coarser resolution maps result in over-estimates of snow cover systematically over the globe. Differences are most pronounced at the snowline. From a synoptic perspective, MOD10C1 (0·05° resolution) and MOD10C1C (0·25° resolution) are similar in mapping snow extent, MOD10C1C, tending to map snow over a broader area at all snow fractions except at 100% fractional snow cover (Figure 8). In effect, the coarser resolution snow map appears to spread over more area and have greater area of lower snow fractions compared to the higher resolution CMG. When scrutinized at local or regional scales, there are significant differences in snow fraction amounts and extent between the CMGs (Riggs *et al.*, 2005). Of course, this is to be expected and is the reason why the finer resolution product, MOD10C1, should be used whenever feasible.

An advantage of the MOD10C1C is that it facilitates comparisons with other coarser resolution products, such as passive microwave snow cover maps (Kelly *et al.*, 2003) and the RUGSL maps [http://climate.rutgers.edu/snowcover/].

AQUA SNOW PRODUCTS

The snow algorithms developed for the Terra and Aqua MODIS instruments are very similar. The major difference is that for the Terra MODIS, band 6 data are used to calculate the NDSI; for the Aqua MODIS, band 7 data are used instead of band 6 because of non-functioning detectors in the Aqua MODIS band 6. This affects the snow algorithm directly because of the different wavelength used (Table II) and indirectly because MYD35, the Aqua MODIS cloud mask, uses Aqua band 7 instead of band 6 as is used in the Terra MODIS cloud mask. However, nearly identical results are obtained in the Terra and Aqua cloud masks (R. Frey personal communication 2005).

The spectral signature of snow is similar in MODIS bands 6 and 7, so the basic nature of the snow algorithm changed only slightly between the Terra and Aqua MODIS instruments. However, the difference in the bands has resulted in subtle differences in the ability of the algorithm to detect snow. Adjustments were necessary in the thresholds of the snow criteria tests for band 7 for the Aqua snow-mapping algorithm so that nearly identical results could be obtained using band 7 in place of band 6 (Riggs and Hall, 2004). In addition, the NDSI/NDVI decision region for snow using Aqua data was disabled because of the uncertain snow detection results found in dense forests using the Aqua snow-mapping algorithm as compared to validated results using the Terra algorithm.

SEASONAL SNOW COVER MAPPING ON THE GREENLAND AND ANTARCTIC ICE SHEETS

In the MODIS snow-mapping algorithm (C4), seasonal snow cover on Greenland is not mapped very well for two reasons. First, the MODIS cloud mask is not very accurate over high-elevation snow covered regions such as Greenland and Antarctica. Secondly, it is difficult to distinguish snow from bare glacier ice using the automated global algorithm. However, in C5, a MODIS cloud-mask-algorithm improvement in the 3·9–11 μm test for cloud in daytime polar conditions has resulted in a significant reduction in false cloud detection over Greenland. This allows for a greatly improved mapping of seasonal snow cover on Greenland, the accuracy of which may be studied via comparison with MODIS albedo (Schaaf *et al.*, 2002) and land-surface temperature (Wan *et al.*, 2002; Hall *et al.*, 2006) maps.

Significant difficulties in cloud detection over snow and ice surfaces are encountered over Antarctica. When cloud is not identified with certainty by the MODIS cloud mask, then the snow algorithm may fail to detect snow because some type of cloud is being imaged and the result is a snow free Antarctic surface. For this reason, the snow maps are not suitable for use in Antarctica.

Antarctica is mapped as completely snow covered in both the daily and 8-day CMG products. The continent of Antarctica is 99% or more snow covered; during the summer, up to 1% of the continent may be snow free but this is not detected on the MODIS snow cover maps. Since the MODIS cloud mask maps clouds over Antarctica most of the time, there are rarely clear pixels for snow mapping.

APPLICATIONS OF MODIS SNOW PRODUCTS IN MODELS

The tile products (MOD10A1 and MOD10A2) are used by investigators as inputs to hydrological models, and have been shown by many investigators to improve model output (Tekeli *et al.*, 2005).

Modelling results by Déry *et al.* (2005) in the Kuparuk river basin (8400 km^2) on the North Slope of Alaska show that improved simulation timing and amount of runoff was achieved when MODIS FSC data are incorporated into the catchment based land-surface model of Koster *et al.* (2000). Another way that the MODIS may be utilized in a land-surface model is to update simulations of snow cover with MODIS snow maps. Through use of this technique, Rodell and Houser (2005) found that the model output compared more favourably with *in situ* snow data than when the simulated snow cover was not updated, even though the MOD10C1 product was degraded to a resolution of 0·25° (~25 km) to facilitate the analysis.

Snow cover depletion curves derived from the MOD10A1, and also the NOHRSC snow products were used as inputs to the Snowmelt Runoff Model (SRM) (Rango and Martinec, 1979) for the Rio Grande (3369 km^2) and the Rio Ojo (995 km^2) basins in 2001 by Lee *et al.* (2005) to simulate streamflow. Both snow maps captured snow extent and progress of snowmelt, but the MODIS product resulted in more consistent snow cover retreat, likely due to the higher resolution (500 m) of the MODIS versus the NOHRSC (1 km) product (Figure 9).

Streamflow forecasts were evaluated for the Snake river basin in the Pacific northwest using the Variable Infiltration Capacity (VIC) macroscale hydrology model. MODIS snow cover maps were used to adjust the model's initial snow state. Inclusion of the MODIS data resulted in forecast error reduction in 59% of the seasonal forecasts and 54% of the 2-week forecasts (Mcguire *et al.*, 2006).

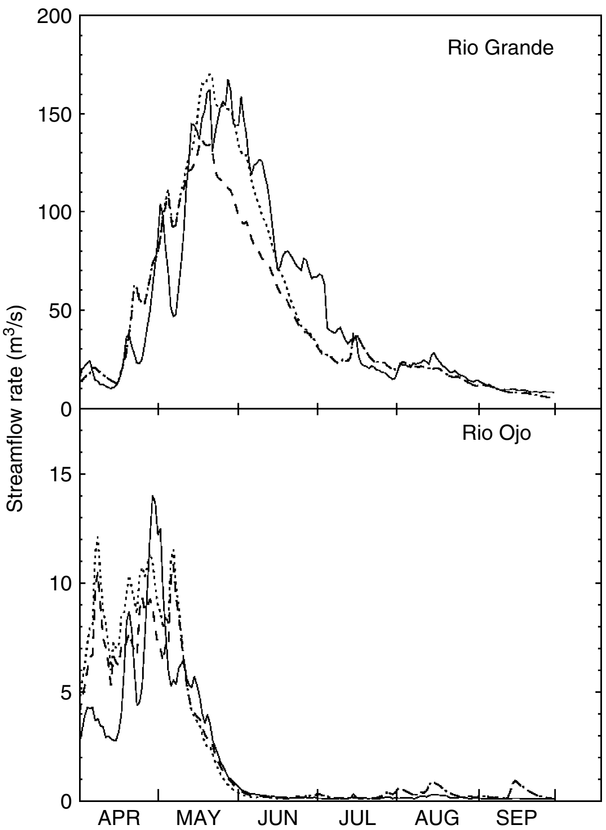

Figure 9. Measured (solid line) and model-simulated streamflow using MODIS- (dotted line) and NOHRSC-derived inputs and the representative parameter values (From Lee *et al.*, 2005)

DISCUSSION AND CONCLUSION

Results from various studies show that the daily MODIS snow maps have an overall accuracy of about 93%, but lower accuracy is found in forested areas and complex terrain and when snow is thin and ephemeral. Very high accuracy, up to 99%, may be found in croplands and agricultural areas. Accuracies of the products cannot be stated by providing just one number per product because the accuracy depends on a number of factors such as time of day, season, land cover and topography.

We have discussed both relative and absolute validation. Absolute validation is generally done on the 500 m resolution Terra swath and tile products, MOD10_L2 and MOD10A1, respectively. The products have been validated against 'ground truth' which often consists of meteorological station or SNOTEL data, but also includes field measurements. Relative validation consists of validating the MODIS products against available operational products (e.g. NESDIS and NOHRSC snow products), most of which have *not* been validated though they are being used extensively with good results.

The validation of the Aqua MODIS snow products is not as advanced as that of the Terra products. This is partly because the Aqua products are more recent, and also because researchers are used to using the Terra products and have not yet started using the Aqua products a great deal. The Aqua validation has, thus far, been based on comparisons with the Terra snow products, and while results show good correspondence in most cases, the use of Aqua MODIS band 7 instead of band 6 does produce some differences in the Aqua snow maps relative to the Terra snow maps, and the accuracy of the Aqua snow products appears to be lower because of this, at least in forested areas.

The Terra MODIS snow products have been validated under both ideal and non-ideal conditions, however it is impossible to validate every snow map that is produced. The largest factor affecting the accuracy of the MODIS snow products is snow cloud confusion. Specifically, the cloud mask tends to map more clouds than are really present.

There is a notable improvement in snow mapping in C5 due to improvement in the C5 cloud-mask algorithm. Comparison of the C4 and C5 snow products has revealed many examples of this improvement in boreal regions where typically more snow is mapped in C5 versus C4 products.

The MODIS snow cover products compare favourably with operational products and represent improvement in terms of resolution, both spatial and spectral, and also in terms of automated snow mapping and cloud masking. Fractional snow cover in the 500 m resolution products, and the addition of monthly 0·05° and daily 0·25° snow map products are important recent product suite enhancements. The availability of the products at three different spatial resolutions (500 m, 0·05° and 0·25°) makes the products easier for users to utilize and employ in either regional and global studies. The fully automated nature of the MODIS algorithms permits the resultant products to be suitable as candidates for climate data records because of the consistency with which snow cover is mapped globally within a given collection, or reprocessing stream.

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